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LA-UR-84-1428

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CONF-840510--6

TITLE: MATERIALS ASPECTS OF SOLAR ENERGY USE IN BUILDINGS

LA-UR--84-1428

DE84 012662

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SUBMITTED TO: AMERICAN SOCIETY FOR METALS CONFERENCE ON MATERIALS FOR FUTURE ENERGY SYSTEMS, WASHINGTON, DC, MAY 1-3, 1984.

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Materials Aspects of Solar Energy Use in Buildings

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ABSTRACT

ADVANCES IN MATERIALS FOR SOLAR ENERGY UTILIZATION have the potential to produce large performance improvements (both present and future concepts) in use of solar energy or conservation. Because approximately 26 quads of the total national energy budget of 75 quads is consumed by buildings, solar and conservation improvements can have a large effect on our overall energy consumption.

There have been a large number of materials research programs funded through the Department of Energy (DOE) in an attempt to expand the use of solar energy. These materials programs have covered the areas of sealants and gaskets, insulations, glazings, glazing-surface treatments, polymers, selective absorber surfaces, phase-change storage, and heat mirrors. In addition to developing the materials, a large effort has been directed toward determining the reliability and durability of solar materials. The present state of the art and status of these solar materials will be discussed.

Although much progress has been made in recent years, many improvements are still needed. For many of the more routine materials, simple cost reductions or durability improvements would suffice. For the more advanced concepts of controlling energy flow into or out of buildings, basic materials research remains a necessity. There are a large number of potentially viable concepts that appear promising but have not yet been developed into usable materials.

INTRODUCTION

THE PURPOSE of this paper is to describe the present status of solar materials development, to outline some of the energy savings that might result from advanced concepts and to describe some of the materials being developed for future uses. It has been shown[1] that there is great potential for advanced concepts and materials. In addition, there are life-cycle cost gains to be achieved through the development of lower cost and more durable materials in the areas of glazings, selective absorbers, storage, and insulating materials.

ENERGY USE IN BUILDINGS

The total 1977 US energy consumption was approximately 75 quads,[2] of which about one-third was consumed by buildings. Of this close to 25 quads, residential buildings accounted for 61% and commercial buildings 39%. Table I describes the breakdown of the energies into end use.

TABLE I
U.S. Building Energy Use by Sector

	Residential	Commercial
Space heating	48%	44%
Space cooling	7	21
Lighting	6	23
Hot water	14	2
Appliances	18	--
Other	7	10
	100%	100%

As can be seen from the breakdown above, solar heating, cooling, and water heating could significantly affect 69% of the residential energy use and 67% of the commercial energy consumption. There are many interrelated effects, particularly with lighting and heating or cooling energies.

HISTORY OF MATERIALS PROJECTS

A Program Plan[3] was developed in 1976 under the sponsorship of the US Energy Research and Development Administration (later, Department of Energy) whose intent was to develop cost-effective systems for solar heating and cooling of buildings. This Plan was then implemented through the release of a number of solicitations aimed at developing the systems, concepts, and materials. The majority of these programs have been completed, and the results of these solicitations have now been published and released. A report[4] describing the materials programs and summarizing the results of these programs has been published by Los Alamos. The materials programs consisted of investigations into absorbers, glazings, adhesives, sealants, insulations, heat-transfer fluids, corrosion, and other stability or interactive studies. These 60 programs have contributed to or developed the present state-of-the-art. Additional programs have been funded by other government agencies, commercial interests, and other DOE solicitations such as the Passive and Hybrid Materials Components Marketable Products Program[5]. There are also programs being funded at the national laboratories, at the Solar Energy Research Institute (SERI), and at universities. Foreign countries have also initiated and are carrying out extensive materials research programs.

POTENTIAL MATERIALS RESEARCH AREAS

To make solar energy more competitive, an obvious approach is to decrease the life-cycle costs of the system. This can be accomplished by increasing the durability or lifetimes, decreasing costs, and increasing the system performance.

Active systems have attained a level in performance where reliabilities, cost reductions, and increased lifetimes are the primary materials problems. While gains in performance are always possible, the immediate increases will probably result from innovative new systems combined with new materials developments that are focused directly on these new systems. In particular, low-cost, durable polymers will find application in advanced systems.

Conservation, passive solar, or hybrid systems share a number of common areas where advances in materials can significantly increase system performances or conserve energy. Neeper and McFarland[1] have analyzed a number of passive systems and locations to determine where some of these materials advances might prove to be beneficial. Additional analyses and results from the Los Alamos passive room[6] testing of advanced concepts have provided additional insight to aid in determining where materials developments are needed.

Some of these are as follows:

- High R glazings and apertures,
- Low-cost selective absorbers,
- Exterior and interior wall treatments,
- Heat distribution and control materials,
- Switchable transparent materials,
- Switchable opaque materials,
- Low-cost durable polymer glazings, and
- High performance, durable (anti-reflective) and (infrared-reflective) coatings on polymers.

HIGH THERMAL RESISTANCE GLAZINGS - Modeling and analysis of a small residential home[1] under various climatic conditions have shown that passive solar systems with high R glazings can work well in adverse climates. Figure 1 describes the energy savings that can be obtained for various glazing R values and solar transmittances for various climates. Although the increased benefits are modest in mild climates, they are significant in extreme climates like Caribou, Maine. Figure 1 shows that even a north-facing evacuated R-12 window can provide some gain in Caribou. Some of the efforts being pursued in high transmittance, high R glazing are aerogels, evacuated glazings, infrared-reflective glazings, and convection-suppression systems.

Aerogels - Research is currently being conducted at Lawrence Berkeley Laboratory (LBL)[7] to produce a window that is both insulating and highly transparent. Aerogel is a very fragile material that must be protected from moisture, shock, and handling. Although aerogels of a number of inorganic oxides[8,9] have been produced, the LBL efforts and those of others are

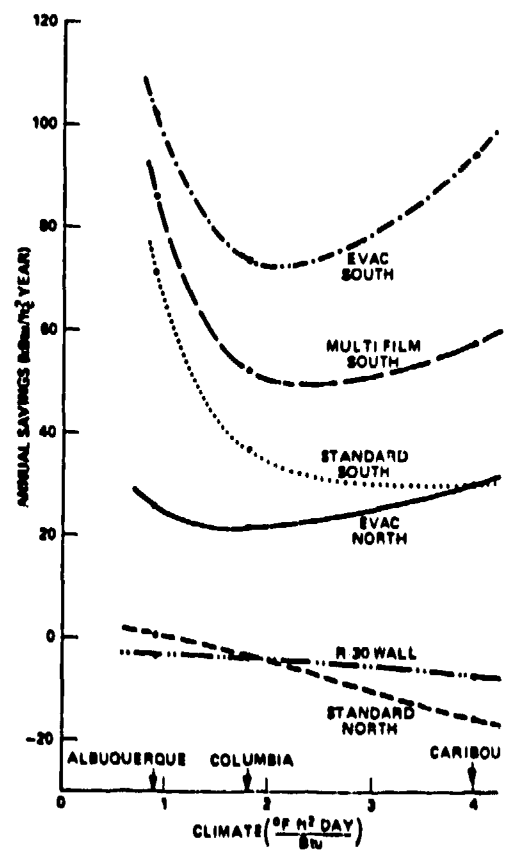

Fig. 1 - Annual energy savings per square foot of Trombe wall with various glazings, plotted as a function of climate. Here, "climate" is defined as the ratio of January degree days to January horizontal insolation. The energy loss of a wall with R-30 insulation is shown for comparison. The three values of climate are for Albuquerque, Columbia, and Caribou.

centered around silica aerogels. Silica aerogels consist of a bonded network of silica spheres, which, with good homogeneity, could have extremely high solar transmittances. To be a practical material it will have to be protected by glass on either side. Transmittances are shown in Figure 2. The dashed curve is a normal-hemispherical measurement while the solid line is a normal-normal measurement. This is indicative of the amount of scattering that is taking place for the shorter wave lengths. Thermal conductivity of air-entrained aerogel is 0.011 Btu/°F h ft while CCl_2F_2 environments have produced values as low as 0.0064 Btu/°F h ft. Based upon the present status, it appears that 0.79-in. aerogel sandwiched between two layers of low-iron glass can achieve a solar transmittance of 0.50 while attaining a thermal conductance of 0.15 Btu/h ft²°F (R = 6.7).

Vacuum Glazings - The Solar Energy Research Institute (SERI) is conducting an exploratory research program to evaluate and produce an evacuated glazing having high transmittance and high thermal resistance.[10] Figure 3 describes one concept under investigation. An optimized glazing system using a combination of the best optical components could conceivably achieve a solar transmittance of 0.70 combined with an R = 12 insulating quality. Evacuated glazing should offer the potential for the highest transmittance glazing and R value for active solar collectors, passive solar systems, or normal window apertures. Other passive systems would have to be evaluated where selective wall coatings would be in direct competition with the heat mirror coatings. In this case, perhaps an uncoated glazing with the selective surface could be the highest performer. On-line processing of a heat mirror coating in a contaminant-free atmosphere, sealed in a vacuum, could maintain extremely good optical properties.

Convection Suppression and Heat Mirrors - Films or devices to suppress the convective heat transfer through windows has been sought for many years through the use of multiple glazings. More recently, high transmittance films have come into being to provide high thermal resistance as well as to attempt to maintain high solar transmittance. A 4-layer glazing using 3M SunGain® is a good example of this approach. Two layers of anti-reflection-treated polyester that have solar transmittances of approximately 0.97 are sandwiched between two layers of glass. Tests of this concept in the Los Alamos passive test rooms have shown better performance than one layer of 0.70-transmittance Heat Mirror® sandwiched between double glazing. Although the conduction through the heat mirror system was lower, transmittance of solar energy through the higher transmittance SunGain® glazing was sufficiently greater to be an overall better performer. A large gain in solar heating fraction could be achieved with a selective surface used in conjunction with the SunGain® units. In addition to these advances, other and better systems of convection suppression than the layered glazings must be developed. These could range from optimized honeycombs to louvered slats.

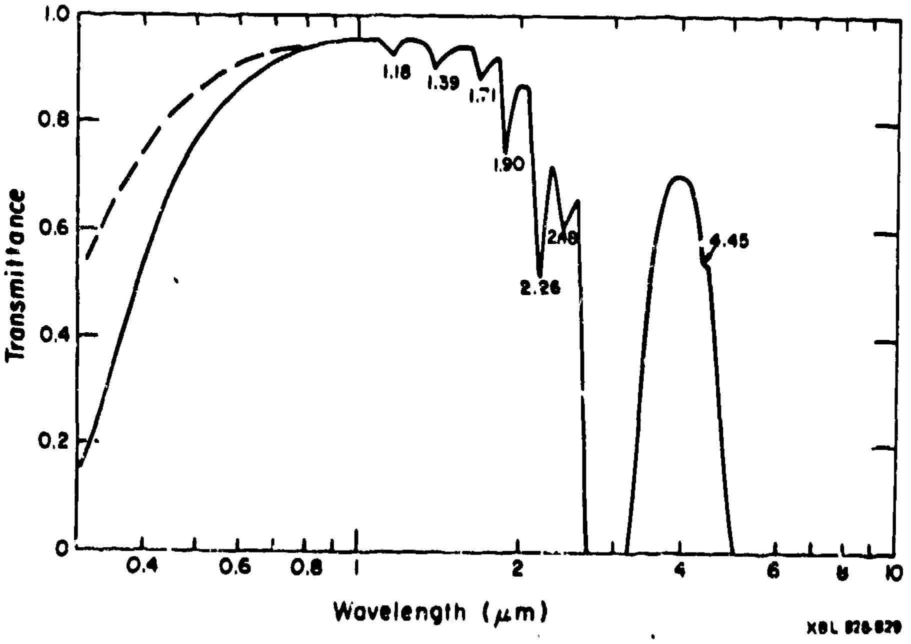

Fig. 2 - Spectral normal-normal transmittance (solid line) and spectral normal-hemispherical transmittance (dashed line) of silica aerogel 4 mm thick. Reference - Rubin, M. and Lampert, C. of LBL.

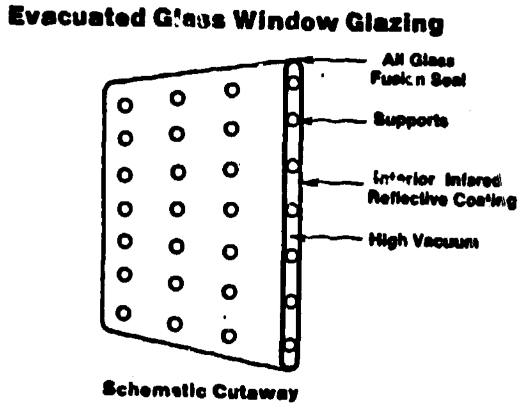

Fig. 3 - SERI Evacuated Glass Window.
Reference - Masterson, K., Benson, D., Christensen, C., Jorgensen, G., SERI.

Materials performance and durability comprise an area of materials research that must be pursued. Anti-reflection and infrared-reflection coatings that have the durability necessary for stand-alone systems, without requiring encapsulation for protection, would be a significant advantage. Infrared-reflecting coatings also have the potential for large performance increases over those currently available. Considerable research is being conducted abroad in an attempt to improve solar transmittance while maintaining good infrared-reflecting properties. Hamberg and Granquist[11] have shown that indium tin oxide (ITO) films coated with a MgF anti-reflection coating are capable of ~95% luminous transmittance and ~10% thermal emittance. Hartig et. al.,[12] have developed a 3-layer oxide/Ag/oxide system which has ~87% transmittance in the visible while maintaining a thermal emittance of ~10%. In addition, there is much room for improvement of inexpensive, durable, high-transmittance polymers for film glazings that might serve as substrates for surface coatings.

SELECTIVE SURFACES - Selective absorbers have progressed considerably since the mid-1970's when black chrome was at its peak of development and commercialization. Nevertheless, black chrome continues to be the standard for durability. Other coatings may be equally durable; however, they do not have the proven track record that black chrome has. Much work still remains to develop an inexpensive coating with good properties and durability for less demanding applications. There is obviously overkill in using a high-temperature durable coating for a low-temperature passive application where more inexpensive coatings may do the job in a more cost-effective manner.

The performance advantage of selective surfaces used in passive systems has been documented in the Passive Solar Design Handbook[13] and in Los Alamos test room reports[7]. Figure 4 describes the advantages of selective coatings over that of black paint for passive systems. This figure shows that for this particular load-to-collector ratio, configuration, and climate, a selective surface system might have an approximate 20% performance advantage over a flat black system. The solar savings fraction (SSF) is the measure of performance used here. Similar advantages have been documented for active systems[14].

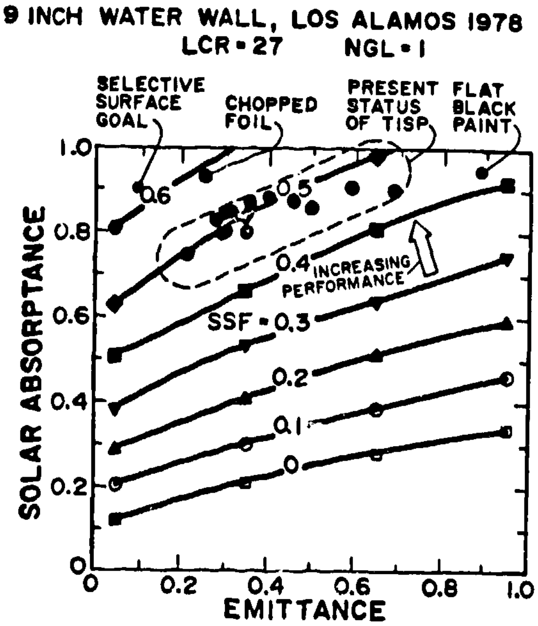

Fig. 4 - Performance comparisons of variable selectivity coatings.

Honeywell,[15] in their studies of inexpensive paints applied to aluminum foil, have produced a product that has the following optical properties: solar absorptance of 0.90 and thermal emittance of 0.10. Durabilities have been investigated and are expected to approach those of black chrome. A production-simulation run of the product resulted in manufacturing costs of $0.22 for the paint applied to the foil, the adhesive backing, and the peel-away protective backing for both the front surface and rear adhesive surface. Although this product has been developed from a research standpoint, it has not yet reached commercialization except for marketing of the paint formulation.

Development of selective coatings that can be easily applied to concrete, masonry, or normal construction materials is yet another area where improved materials are needed. Present day techniques require that concrete be grouted, smoothed, and prepared to receive a selective film that is adhesively bonded to the surface.

Thickness-insensitive selective paints (TISP) research undertaken by Honeywell in 1978 has not attained the necessary properties to make these paints really cost effective. Figure 4 shows the degree of progress that has been made at Honeywell and Los Alamos and the goal that would be desirable for a TISP system. Such a paint system most desirable is a typical metallic flake paint that could be sprayed on any type of substrate. Other inexpensive coatings may also provide the necessary cost effectiveness for low-temperature passive systems.

LOW-EMITTANCE INTERIOR WALL OR CEILING TREATMENTS - Low emittance or high infrared reflectance commercial coatings are presently being marketed as energy conservation coatings for reducing building energy consumption. When these coatings are combined with solar passive systems, the results are even more dramatic. This is primarily because of the large surface area radiators like mass storage walls. Data from solar mass wall test rooms at Los Alamos are showing an approximate 30% auxiliary energy saving realized by using low emittance surfaces rather than the conventional high emittance surfaces. Evaluations of the energy and human comfort parameters are needed to determine how to obtain the greatest benefits from high infrared-reflective surfaces. These benefits could range from basic energy savings to implementing or assisting in energy transport.

SWITCHABLE COATINGS - Glazing Materials - Neeper and McFarland[1] presented the modeling results for a number of solar geometries having switchable optical properties. Of these, one of the most representative was application of a switchable glazing to a south-facing Trombe wall system. They show that, for the given system, assume glazing optical properties could be switched from solar transmittance of 0.7 for the standard case to 0.1, and solar reflectance of 0.8 when the room temperature increased from 70°F to 73°F. This scenario reduced the June through September cooling loads to about 0.2 of that normally encountered without significantly affecting the annual solar heating savings. Similar savings in cooling loads resulted from the analysis of direct gain or window-glazed systems. This control strategy did, however, significantly reduce the annual solar heating performance of the direct gain system.

A number of investigators have been pursuing selective transmission materials. Primary efforts to date have been centered around photochromic, thermochromic, electrochromic, and liquid crystal approaches. Although much of the materials research for solar applications is still in its infancy, many of the materials and concepts show promise.

The requirements for solar applications differ substantially from the present electronics display applications where changes in the visible portion of the spectrum are of primary interest and the switching rates are extremely fast. SERI,[16] LBL,[17] and many other investigators[11,18] have begun to look at switchable materials for solar applications. Some of the most recent studies by SERI have shown that a WO_3 stack of electrochromic material displayed a 68% reduction in spectral transmittance at a wavelength of 600 nm and a Deb's[19] cell went to a virtually opaque level. Both cells had only about a 25% solar-weighted, non-colored transmittance. Presently known changes proposed by SERI should improve the transmittance of this type of coating to over 50%. Svensson and Granquist[10] have recently demonstrated that a reversible shift from 12 to 86% solar transmittance is possible. Longer term research and improvements would obviously be expected to produce far better properties. In addition, there are many ranges of switching that can be visualized for the various operating modes. As proposed by Benson at SERI, some of these might be multiple and independently switchable stacks. Some of the operating modes might be:

- Visible light transmitting only for summer daytime operation.
- Solar spectrum transmitting only for winter daytime operation.
- Completely reflecting for winter nighttime operation.
- Completely transmitting for summer nighttime operation where $T_{amb} < T_{inside}$.
- Transmitting in the 8 to 13 micron range for summer radiative cooling.

Switchable Exterior Coatings - An analytical evaluation was conducted at Los Alamos to determine if exterior paints or coatings whose optical properties could be switched would improve the annual thermal performance of buildings. The concept assumed that a material could be developed whose solar absorptance and/or infrared emittance would change at a given temperature to benefit either heating or cooling. These coatings could be directly switched by temperature or by sensing temperature and switching by other means. Several climates (Phoenix, St. Louis, and Minneapolis) were evaluated, as were construction mass and insulations. The optimal switch temperature was found to be 60°F. Table II shows that a reasonably well insulated building gains only a small amount from the switch in properties; however, poorly insulated buildings, typical of many retrofits, could benefit signigicantly.

Honeywell[20] has studied thermally and field-effect switched VO_2 and NbO_2 to develop a solid-state, infrared optical chopper. Although this application is far different from that for solar, and the spectral changes would have to be modified for solar applications, it is interesting to note the magnitude of the changes that have resulted. Temperature-induced-absorption changes occur in the 2.5 to 6.0 micron spectral range for temperatures ranging from ambient to 200°C for single crystal NbO_2. Varying the temperature from 25°C to 200°C results in corresponding changes in transmittance of ~60% to ~10% at 2.5 microns. Reflectances show a corresponding change but to a slightly lesser degree. Obviously there is a long way to go from basic phenomenon to the ideal solar application.

Switchable Interior Opaque Coatings One application of switchable emittance coatings is that of energy-flow control from storage to the

TABLE II

CHANGE IN ANNUAL AUXILIARY[a]

	Phoenix	St. Louis	Minn.
Light Construction			
R-20 Walls & Roof	- 8.3%	- 6.4%	- 4.7%
R-11 Walls & Roof	-13.5	- 9.6	- 7.0
R-2.5 Walls & Roof	-24.4	-15.0	-11.0
Medium Construction			
R-20 Walls & Roof	- 8.4	- 6.5	- 4.7
R-11 Walls & Roof	-13.7	- 9.7	- 7.0
R-2.5 Walls & Roof	-25.4	-15.3	-11.0
Massive Construction			
R-20 Walls & Roof	- 8.9	- 6.7	- 4.8
R-11 Walls & Roof	-14.2	- 9.8	- 7.0
R-2.5 Walls & Roof	-25.4	-15.3	-10.8

[a]Change in energy is based on a COP=1 for auxiliary heating and cooling and normal surface properties of $\alpha_s = 0.5$ and $\epsilon = 0.9$. Switchable properties vary from a selective absorber $\alpha_s = 0.9$, $\epsilon = 0.1$ to a selective reflector $\alpha_s = 0.1$, $\epsilon = 0.9$.

room space for passive systems. In passive systems, energy flow from a storage mass wall is transported primarily by convection and radiation. The radiation portion of this energy transport can be as much as two-thirds of the total energy transport in closely radiation-coupled systems. By varying the emittance of the wall through the use of switchable coatings, either electrochromic, thermochromic, or other means, the building living-space temperatures could be controlled.

Additional materials activation schemes could possibly be used to control boundary layers or dead air spaces for convection suppression as well. For large solar systems, much of the heat delivered to the living area is vented because of overheating. Much of this vented heat might be conserved for later use if the proper controls were available. This could apply to both radiation and to convection.

FUTURE PROSPECTS

There are a number of new materials advances that could significantly increase the performance of solar energy in buildings. A number of these could be applied to passive, active, or hybrid systems.

- Cost effectiveness increase for present systems and materials through achievement of greater durability, lower costs, or better performance.
- High thermal resistance/high solar transmittance glazings or aperture materials that would permit south glazings to be operated more efficiently or east, west, and north apertures to provide significant gains.
- Switchable glazings that, by changing absorptance and thermal emittance can be used benefically to accept winter heating energy or reject summer excess heat.
- Optically switchable opaque coating that can be used to absorb in a heating mode or reject heat in a cooling mode.
- Switchable emittance coatings that can be used within the building envelope to control energy flows from storage to living areas.
- Low emittance room coatings combined with solar passive systems should be investigated to assess possible benefits.
- Storage materials that might use controlled super cooling or chemical changes to return to higher temperatures on demand for more controlled release of energy.
- Solid-solid phase change materials that might be used to replace dry wall or other materials for added heat storage.
- Building opaque surface or aperture heat rejection that would make use of the 8-13 micron atmospheric window needs further investigation to see which concepts and materials requirements might be developed into practical systems.
- Inexpensive selective absorbers that can easily and inexpensively be spray- or brush-coated on concrete, masonry, or storage materials.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge all of those who provided information for this report, in particular C. M. Lampert of LBL and Dave Benson of SERI. Many thanks go to Gloria Lazarus for computer simulations and graphics. We are particularly appreciative of the word processing by Carole Oldenborg and Sandy Dixon and editing by Sherry Reisfeld.

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